Reducing slab boundary artifacts in 3D multi-slab diffusion imaging by jointly estimating slab profile and image

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Purpose:

Multi-slab 3D acquisition for diffusion imaging has potential for achieving thin slices and high SNR efficiency[1-4]. However, multi-slab imaging suffers from slab boundary artifacts due to saturation effects, aliasing and B0/B1 inhomogeneity (Fig. 1 a). As demonstrated in another abstract from our group (see Fig. 3), these artifacts are not purely multiplicative and propagate through to quantified diffusion metrics despite normalization of diffusion-weighted images with a b=0 image. Previous work has aimed to reduce slab boundary artifacts by overlapping and oversampling slabs during acquisition and combining overlap regions as part of reconstruction[3] (Fig.1 b). This method can avoid aliasing artifacts with sufficient oversampling, but the scan time is significantly increased and saturation effects remain. Recently, slab profile encoding (PEN) was proposed to remove the aliasing artifacts with a minor increase in scan time[4]. However, the PEN reconstruction also retains saturation effects, leading to significant signal modulation at slab boundaries for TRs achieving optimal SNR efficiency (1–2s). To date, the most compelling multi-slab 3D images have required the use of less efficient TRs (≥4s). In this work, we propose a nonlinear reconstruction method to remove the slab boundary artifacts from a range of sources, which is compatible with optimal TRs.

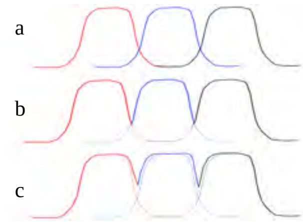

Fig. 1. An example of a) excitation profile for 3 slabs, b) Direct combination and c) PEN reconstruction.

Methods:

Reconstruction algorithm. The signal equation for multi-slab imaging can be formulated as: $PFSu = d$ [1]
with image u, slab profile S, Fourier transform F, k-space sampling P, data d. If S is known, eq. [1] represents a linear system, which can be solved directly by standard approaches (e.g. least squares/pseudo inversion). However, the estimation of the slab profile is not straightforward due to dependence on partial volume, field inhomogeneity, etc (see accompanying abstract). Existing methods, such as Bloch simulation and estimation from a calibration scan[4] were not able to provide a satisfactory slab profile. In this work, a new method is proposed to jointly estimate the slab profile S and image u. We treat both slab profile and image as unknowns, $x = [u, s_1, \dots, s_N]^T$, thus transforming eq. [1] into a nonlinear inversion that we solve using iteratively regularized Gauss Newton Method (IRGN)[5]. Three constraints are considered in the reconstruction: 1) the solution should be close to the PEN result, 2) the slab profile varies slowly within the slice plane, 3) slab boundary artifacts occur at known spacing in the slab direction, reflected in spikes at particular frequencies. Each of these constraints was translated into an error term in the cost function for non-linear optimization. At each step, given x_n (containing slab profile and image estimates, s_n and u_n) from the previous step, the update dx is calculated by solving the minimization problem:

$$min \parallel E'(x_n)dx - (d - E(x_n)) \parallel^2 + \alpha_n \parallel x_n + dx - x_0 \parallel^2 + \beta_n \parallel W_c F(s_n + ds) \parallel^2 + \gamma_n \parallel W_u F(u_n + du) \parallel^2 \quad [2]$$

E is a nonlinear operator $E(x) = (PF(u \cdot s_1), \dots, PF(u \cdot s_N))^T$. W_c and W_u are weighting matrices imposing in-plane smoothness and minimizing spikes along kz. The regularization parameters α_n, β_n and γ_n are reduced in each step. Minimization uses the conjugate gradient algorithm, with step updates $x_{n+1} = x_n + dx$.

Data acquisition. In vivo data from two healthy subjects were acquired with a Siemens Verio 3T scanner using a multi-slab readout segmented EPI sequence[2, 6]. Sequence parameters: 220mm×220mm×120mm FOV, 1.5mm isotropic resolution, TR/TE = 2000/78ms, 9 slabs with 10 slices/slab, overlap/oversample ratio = 0.2/0, GRAPPA factor 2, number of readout segments 3 (with 3/5 readout partial fourier acquisition), b = 1000 s/mm^2, 20 directions with two b=0 images. Total scan time was 22 minutes.

Results:

Three methods are compared for the reconstruction: 1) direct combination, where the upper- and lower-most slices for each slab are discarded and the remaining slices concatenated, 2) PEN reconstruction and 3) our proposed method. The results are shown in Fig. 2. The direct combination results have strong artifacts at the slab boundaries, even in the FA image (where diffusion-weighted images have been normalized by the b=0 image). PEN reconstruction removes the aliasing signal, reducing slab boundary artifacts, but there still exists obvious signal drop in b=0 and DWI image and residual artifacts in the FA and color map (shown by the yellow box). The proposed method significantly reduces the slab boundary artifacts in both the raw images and derived diffusion metrics.

Discussion and Conclusion:

A nonlinear reconstruction method was proposed to correct slab boundary artifacts. By jointly estimating the slab profile and image content, an image with reduced slab boundary artifacts can be generated. The results demonstrate the superior performance of the proposed method over other methods. Besides diffusion imaging, the proposed method can also be applied to other imaging methods using multi-slab acquisition.

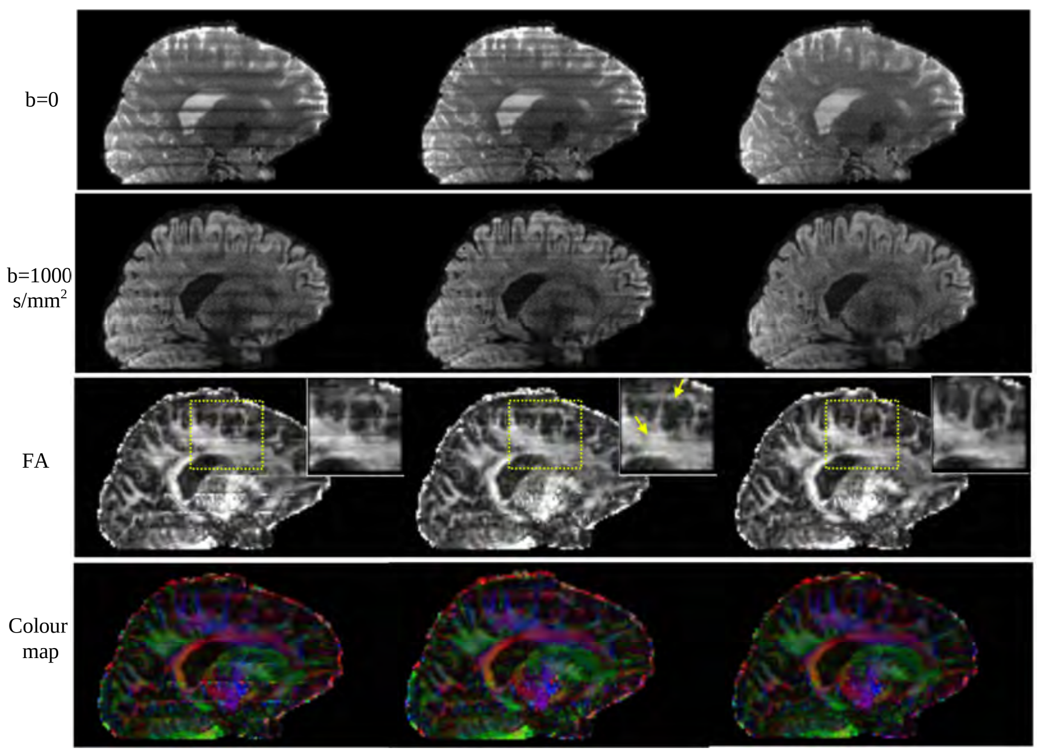

Fig. 2 Reconstruction results of direct combination, PEN and the proposed method.

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